

AC Mini-Grids

The Future of Community-Scale Renewable Energy

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This 3,600-watt photovoltaic array is part of a groundbreaking “AC mini-grid” system in Bulyansungwe, Uganda.

For decades, nearly all small-scale renewable energy (RE) installations have been DC-coupled systems. These DC-based systems are just like you read about in *Home Power*—where one or more DC sources like photovoltaics (PVs) and/or wind generators are used to charge batteries that, in turn, power DC loads directly, or AC loads via an inverter. Each charging source requires a controller to regulate the power from the RE source to the battery. While DC coupling is still the state of the art in most of the world, a method of AC coupling (connecting several charging sources together on the AC side of the system) has been developed that offers significant benefits for certain applications.

AC coupling uses batteryless inverters networked to one or more centralized battery-based inverters. This configuration allows AC to either go directly to AC loads, bypassing the batteries, or to charge the batteries via the battery-based inverter. Regulation is done on the AC side of the system by limiting the output of the batteryless inverters when the batteries are fully charged.

I had the unique opportunity of working with this new technology for my thesis project while doing graduate studies in renewable energy in Germany. My project was the design

and installation of a PV and engine-generator hybrid system with an AC mini-grid. The system powers a rural boarding school complex in the village of Bulyansungwe, Uganda, where there are no utility lines within several miles. The people of Bulyansungwe are primarily subsistence farmers who grow bananas and coffee as cash crops. Bulyansungwe Secondary School is considered the center of the village because there is no conventional village center of houses and shops.

The school complex includes a girls' dorm, boys' dorm, classrooms, a convent, and a social center. The German organization, Together: Assistance for Uganda, has provided funding for its construction and operation. Previously, the only source of electricity was a small, gasoline-powered generator used on special occasions.

Hybrid Systems & Mini-Grids

Hybrid renewable energy systems have proven to be an excellent solution for providing electricity to areas with no utility service. Hybrid systems combine multiple sources to supply steady and reliable energy to consumers. Common system configurations often include one or more renewable

energy sources (PV, wind, etc.), battery storage, and an engine generator for backup.

The majority of existing hybrid systems are DC-coupled, where all the electricity sources are connected to a single battery bank. The loads are then either powered directly from the battery bank or via AC from inverters. Recently, however, pilot projects and new installations have shown the technical feasibility of AC coupling.

An AC mini-grid is expandable and modular with standardized system components. Every system component (energy sources, consumers, and storage) is connected to a single AC grid. This allows the use of established residential AC standards for interconnection of the different devices. This is in contrast to DC-coupled systems, where there is no such standard and a wide variety of system voltages are common.

Adding more PV or battery to an AC-coupled system is as simple as installing that new component and connecting it to the grid without any modification to the original system. In the case of DC-coupled systems, modifications (sometimes significant) will need to be made to the original system.

Comparison of AC- & DC-Coupled Systems

This AC mini-grid concept is also often referred to as modular system technology. Since each component is connected to the grid, a sort of modular power plant can be constructed. A major advantage to such a system is that it can easily grow to meet increased consumption demands simply by adding more producers to the grid.

Estimating future electrical needs can be extremely difficult (especially for large systems), and often leads



Courtesy Franz Kinninger

The author on the completed PV array, with the Sunny Boy, batteryless inverters visible in background. This array is 75 feet (23 m) from the battery bank.

A view of the completed PV installation above the large school compound. An AC mini grid allows optimal placement of system components without the proximity restrictions inherent in DC-coupled systems.

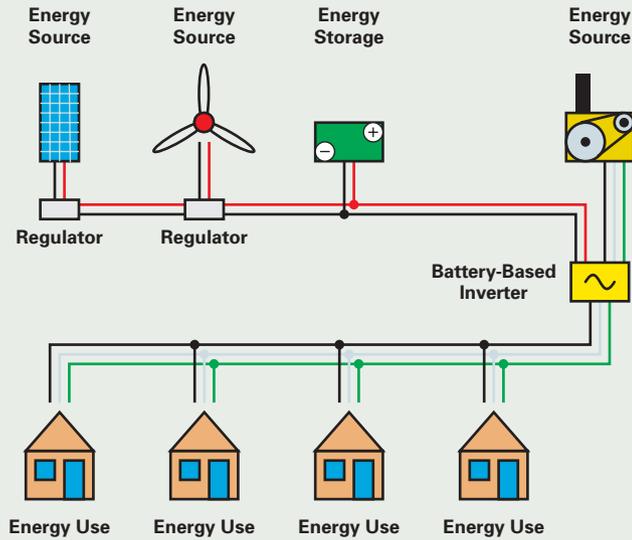


to underdesign or overdesign (poor supply or poor economics). Modular system technology is potentially a great solution because the supply can more easily grow with the demand.

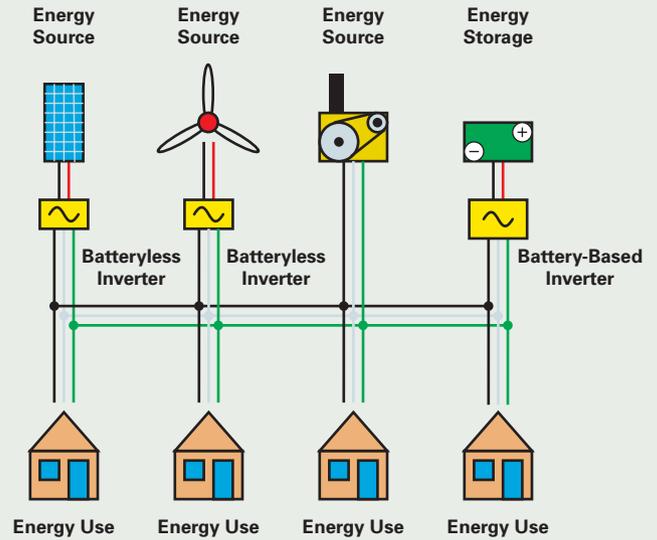
Another attribute of AC mini-grids is their ability to be interconnected. Since they operate under common parameters, multiple systems can easily be combined simply by connecting their AC lines. In this way, small individual systems can be connected to form village grids, and village grids can be connected to form regional grids. Interconnection of systems results in greater overall security of supply because of the redundancy of suppliers.

AC mini-grids can also be incorporated into a utility grid at any time simply by connecting directly to the utility lines. This can be an important advantage in many areas where rural utility grids are expanding

DC-Coupled System



AC Mini-Grid System



rapidly. It's important to note that mini-grids are not dependent on the interconnection, and can continue normal operation in the event of line failure.

A potential disadvantage to AC mini-grids as opposed to DC-coupled systems is a slightly lower system efficiency. This is a result of more frequent conditioning of the electricity because all energy stored in the batteries must be rectified during charging and inverted during discharging. This effect is greatest in systems where a large percentage of the consumption is at a different time than the production

(such as in PV systems with high consumption at night) because more of the energy must be stored in the batteries.

System modeling suggests, however, that this is a minor influence in system performance, and less important than engine-generator operating time and precise sizing of the energy producers. One set of simulations had slightly more than 50 percent of the PV energy flowing through the batteries. The end result was a PV array performance ratio of 0.54 for the DC-coupled configuration and 0.51 for the AC-coupled configuration.

The SMA Sunny Island inverter, battery bank, generator connection box, and two AC distribution boxes.



Implementing the Technology

The most important technical challenge of AC mini-grids is coordination of the different components, especially the battery-based inverters because they are generally the grid-forming units. The inverters must have exactly the same phase and frequency, and share the charging and discharging equally. Traditionally, this has been done through high-speed, hard-wired communication—one master inverter dictating the operation of the other inverters through a separate communication network.

While this can allow for expandability in localized systems, it is not sufficient for interconnection of multiple systems without considerable reconfiguration of the components and communication network. In addition, this system concept has little redundancy because it is completely reliant on the operation of the master unit.

Through a cooperation of German organizations, a method has been developed for multi-master operation. This new technology uses the grid frequency and voltage as a communication medium. The resulting characteristics are quite similar to those of rotating generators and motors. Known as "drooping," the frequency drops slightly from nominal with loading and rises slightly during battery charging. Reactive power information is exchanged in the same way through slight variations (drooping) in the

voltage. In other words, the multi-master inverter is able to regulate the output, based on communication between the inverters in the system.

This new technology allows for a completely modular system configuration and enhanced security through parallel multi-master operation. Each battery bank is controlled by its own master inverter, and PV arrays are connected using standard, batteryless string inverters. This technology has been integrated into some of SMA's Sunny Island battery inverters for the European market. However, the multi-master technology is not yet included in the Sunny Islands recently released in the U.S. market. The Sunny Island 4248U has AC-coupling technology, but is not capable of multi-master operation.

Generator Connection

Engine-generators can also be easily incorporated into the AC mini-grid. With proper control electronics, a generator can be directly connected to the AC grid and operate autonomously within the system. However, these control electronics are currently prohibitively expensive for most systems, so the generator is commonly controlled by the battery-based inverter.

A close-up of the SMA Sunny Boy inverters and a junction box that combines their AC output.



Tech Specs

Overview

System type: Off-grid PV & engine-generator hybrid system

System architecture: AC mini-grid, 230 V, 50 Hz

Location: Bulyansungwe, Uganda

Solar resource: 5.0 average daily peak sun hours

Production: 485 AC KWH per month

Photovoltaics

Modules: 48 Shell Solar S75, 75 W STC, 17.6 Vmp, 12 VDC nominal

Array: Four, 12-module series strings, two parallel strings feed each inverter, 3,600 W STC total, 211.2 Vmp

Array installation: Locally constructed steel frame tower, facing north with a 15-degree tilt angle

Energy Storage

Batteries: 30 Exide Sonnenschein, type 6 OPzV 360, gel, lead-acid, 2 VDC nominal, 360 AH at 100-hour rate

Battery bank: 60 VDC nominal, 21.6 KWH total

Balance of System

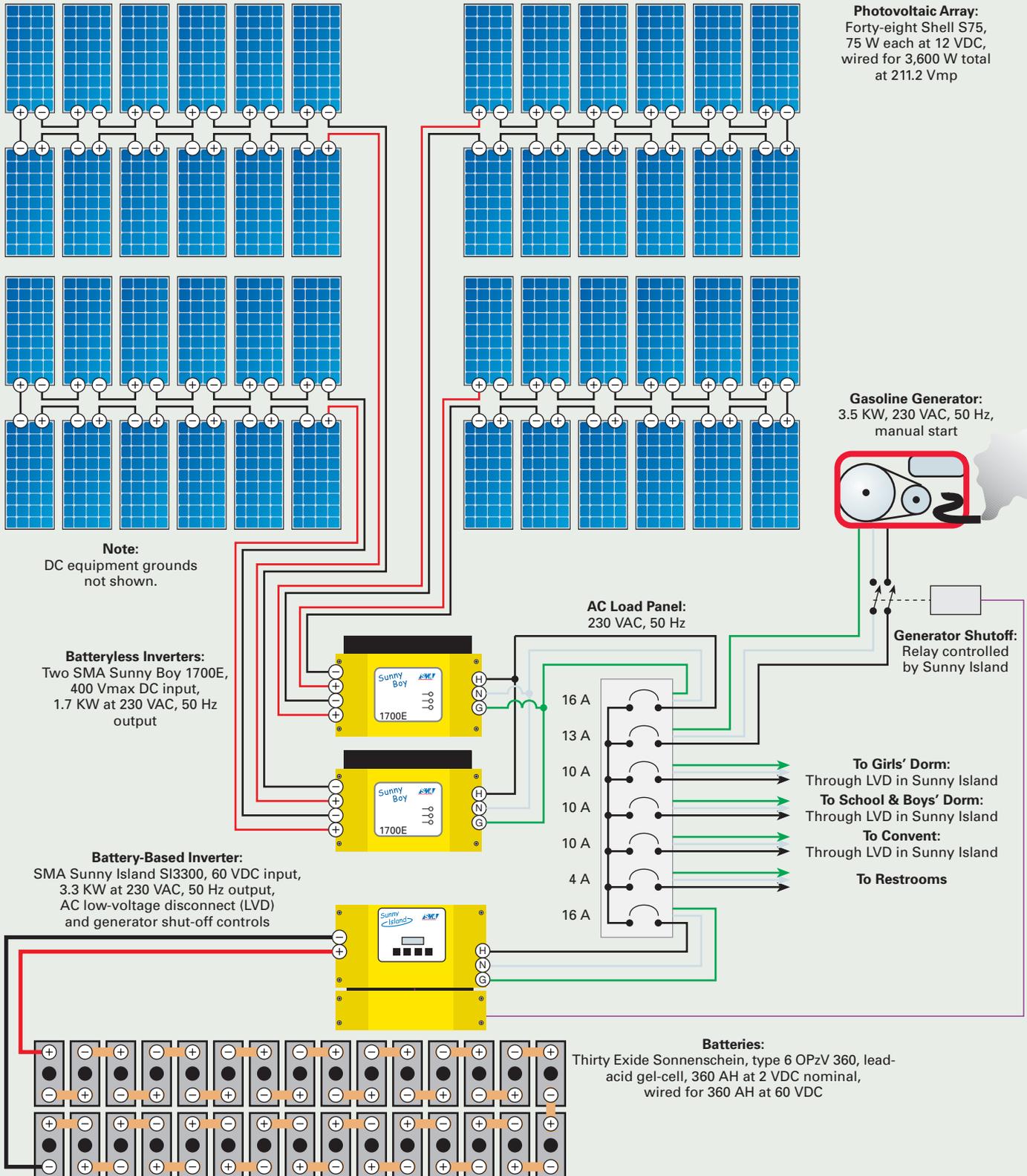
PV inverters (batteryless): Two SMA Sunny Boy 1700E, 1.7 KW, 400 VDC maximum input voltage, 139–400 VDC MPPT window, 230 VAC, 50 Hz output

Battery-based inverter: SMA Sunny Island SI3300, 3.3 KW, 60 VDC nominal input, 230 VAC, 50 Hz output

Engine generator: 3.4 KW, 230 VAC, 50 Hz, manual start, gasoline fueled

Once connected, a generator works naturally with the voltage and frequency droops. Excellent load sharing among SMA's battery-based Sunny Island inverters and a diesel generator have been demonstrated in the HYBRIX (hybrid system) demonstration plant in San Agustin, Spain. It is common for island inverters to switch into a grid-supporting mode when a generator is connected. This is not necessary with the variable voltage and variable frequency operation of the Sunny Island units, so the inverter remains in grid-forming mode. This allows the system to provide the sum of the peak powers of the inverter and generator.

Bulyansungwe School's AC Mini-Grid System



Note: All numbers are rated, manufacturers' specifications, or nominal unless otherwise specified.



Courtesy Franz Kininger

The author trains Julius, a local technician who is now responsible for the operation of the system. The financial director looks on—both are alumni of the school.

Bulyansungwe System

The Bulyansungwe system is an AC mini-grid. The installation consists of PV and gasoline hybrid generating capacity with an integrated ultraviolet water purification and pumping system. It supplies both electricity and clean water to the school complex.

The primary electricity is supplied by a 3.6 KW PV array, which is connected to the mini-grid through two SMA Sunny Boy 1700E inverters. Energy is stored in a 21.6 KWH battery bank. The connection of the battery bank to the mini-grid, as well as the general control and orchestration of the system, is performed by a 3.3 KW SMA Sunny Island inverter (European model SI3300).

The Sunny Island communicates with the Sunny Boys via grid frequency similar to the droop system described earlier. If the batteries are fully charged, the Sunny Island will instruct the Sunny Boys to derate their power output so that the batteries will not be overcharged. Backup is provided by a 3.5 KW pull-start gasoline generator that was already owned by the school. There are plans for a self-starting diesel generator when funds are available.

The first phase of the system is now in full operation, supplying electricity and water to the girls' dorm, boys' dorm, classrooms, and convent. The primary use of the electricity is lighting. The dining room is open in the evening for studying, and hall lights are a huge help for midnight visits to the restroom. Another important use is kitchen appliances, such as blenders and mixers. However, the stereo is by far the students' favorite use of their new energy.

Bulyansungwe's social center was left unelectrified because it is presently only used during the day. However, plans to establish a health center and basic hospital that will require electricity are in the works. This is one of the reasons an AC mini-grid is so appropriate for this location.

Three years before we installed the AC mini-grid, the sponsoring organization installed a small, DC water pumping and purification system in the social center in Bulyansungwe.

This separate, DC system is powered by twelve, 75 W PV panels, with two, 130 AH batteries for storage.

When the health center is realized, the existing DC system will be converted to AC and connected to the current mini-grid. More PV panels will be erected and the combined PV array will be connected to the mini-grid through a Sunny Boy inverter. Another Sunny Island inverter, which will allow the two systems to function together, and a battery bank will also be installed in the social center. The system will operate as a multi-master, frequency-coordinated AC mini-grid.

Expandable & Modular

The AC mini-grid topology of the Bulyansungwe system will also make future expansion of the system to meet growing energy demands easier. For example, if the school were able to acquire a few computers for classroom use, the daily energy demand would increase. This might necessitate more PV generating capacity, but not more battery capacity, since the computers are used during the day.

With the AC mini-grid, a small PV array could be added to the system by using a standard, batteryless, grid-tie inverter and connecting its output anywhere on the grid. The PVs could be mounted near the school building, which is a couple hundred yards from the current PV array and battery bank in the girls' dorm. Mounting the supplemental system near the school building would reduce line losses over that distance. This is in contrast to DC-coupled systems, where more significant reconfiguration of the system might be necessary for expansion.

AC mini-grids that are equipped with multi-master operation are an exciting new advancement in off-grid PV technology. This new technology opens the door to interesting new possibilities in hybrid system design. The plans for expanding the Bulyansungwe project highlight expandability as a primary benefit to AC mini-grids.

Access

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